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A WIDE-FREQUENCY-RANGE AIR-JET SHAKER

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SUMMARY

A simple shaker which obtains its driving force from streams of high-velocity air is described. This air-jet shaker has the following advantages: its force can be calibrated statically and appears to be constant with frequency; it is relatively easy to use; and it has essentially massless characteristics. With this shaker it is possible to define the unstable branch of a frequency-response curve obtained with a nonlinear spring.

INTRODUCTION

The excitation of true vibration modes and natural frequencies of airplane wings, empennages, and control surfaces is often difficult, if not impossible, because of the added mass of the exciting mechanisms commonly available. This problem becomes particularly acute when the mass of the shaker is large with respect to the mass of the elastic body. Attempts to circumvent this difficulty by use of air-jet shakers have been largely unsuccessful, as pointed out in reference 1, because of their limited frequency range. In the air-jet shaker of reference 1, the airstreams were pulsed by means of a rotating valve in the air-supply line. Because of the inertia of the air in the supply line, this arrangement resulted in a driving force which dropped off rapidly with increasing frequency. In order to overcome this frequency limitation, the air-jet shaker described herein was designed so that it used external interruption of the air jets rather than internal pulsing of the airstream.

This paper presents a description of the air-jet shaker, some experimental data obtained with the shaker, and a discussion of possible uses and limitations of the shaker.

SYMBOLS

A cross-sectional area of nozzle, sq in.

a width of jet opening, in.

b   distance from nozzle to interrupter, in.

d   distance from center of jet to edge of flat plate, in.

F   force, lb

g   structural damping coefficient

l distance from jet to flat plate, in.

p_t stagnation pressure of jet, lb/sq in.

w   mass flow through nozzle per unit time, $\rho A V$

x   amplitude

V   stream velocity, ft/sec

ρ air density, slugs/cu ft

ω circular frequency, radians/sec

θ angle between flat plate and plane normal to axis of jet, deg

Subscripts:

max   maximum

st   static conditions

n   nth natural mode

LIMITATIONS OF OTHER SHAKER DESIGNS

The conventional types of shakers used to excite vibration modes and natural frequencies of airplane wings, empennages, and control surfaces are usually mechanical or electromagnetic shakers. These shakers must be attached to the test specimen; thus, mass is added to the specimen. Because of this addition of mass, these shakers cannot be used for very light specimens without affecting the natural frequencies and mode shapes. The location of the shaker also is significant when these shakers are used, since the vibration mode shapes vary with the location of the shakers. The force input is difficult to control; thus, true frequency-response curves are not easy to obtain.

In order to overcome the limitations of the mechanical and electromagnetic types of shakers, air-jet shakers have been devised. (See ref. 1.)

Because of the inertia of air in the supply line of the shaker of reference 1, the driving force decreased with an increase in frequency. Because of this frequency limitation, the type of jet air-shaker described in reference 1 proved to be unsatisfactory except at relatively low frequencies.

DESCRIPTION OF SHAKER

An air-jet shaker which derives its driving force from the kinetic energy of streams of high-velocity air impinging upon the test specimen has been designed and is described herein. A sketch of the shaker is shown in figure 1.

The air flow to the nozzle is controlled by a valve and a pressure gage. The nozzle used for the force test was a rectangular converging nozzle measuring 0.5 inch by 0.045 inch at the throat. (The small gain in efficiency to be expected of a supersonic nozzle - approximately 7 percent at a gage pressure of 100 pounds per square inch - was not considered to be sufficient to warrant the increased difficulty of making a supersonic nozzle.)

The airstreams exit from the nozzles at a constant velocity and pressure. The airstreams are then interrupted by rotating cams which pulsate the two airstreams 180° out of phase. The frequency of the pulses can be controlled with any suitable variable-speed motor driving the rotating disks. The magnitude of the oscillating force can be varied by the pressure or flow-regulating valve in the air-supply line.

Measurement of structural damping of an elastic body sometimes requires that the oscillating force be withdrawn instantaneously in order that the rate of decay of the oscillations may be observed. This cutting off of the force may be accomplished at low frequencies by a quick-acting shut-off valve in the air-supply line or at high frequencies by means of solenoid-operated baffles inserted into the airstream as indicated in figure 1.

For some applications of the shaker, the shape of the forcing function is not critical and a simple cam, such as that shown in figure 2(a), would be satisfactory. This type of cam would result in a square wave of high harmonic content. A sinusoidal force may be obtained by use of a rectangular nozzle in conjunction with a cam similar to that shown in figure 2(b).

The complexity of the motor-speed control depends upon the use for which the shaker is intended. In applications where accurate control of the frequency is not required, variation of the voltage to an electrically driven motor may prove to be satisfactory. For multiple-shaker

arrangements, synchromotors may be incorporated to turn the interrupter disks. These motors can be driven in phase or 180° out of phase by a synchromotor generator located in a remote control box. It should be pointed out that the interrupter disks must have an odd number of lobes in order to effect a 180° phase shift in the air jets. Since the power required to turn the interrupter disks is very small, the synchromotor generator can be driven by commercially available variable-speed friction drives.

The force of the air jets may be nearly doubled, if necessary, by attaching a light-weight Pelton-type bucket to the elastic body in order to effect a 180° change in the airstream direction. Large force outputs, however, generate much noise.

EXPERIMENTAL RESULTS

In order to determine the performance characteristics of the air-jet shaker, simple force tests were conducted to determine the shape of the disk interrupter required to obtain sinusoidal force outputs and the effects of specimen diameter, of distance from air jet to test specimen, and of the proximity of the edge of the test specimen.

The ordinates of the cam required to produce sinusoidal force were determined experimentally by measuring the static force exerted by the airstream upon a flat plate mounted normal to the airstream while the exposed jet area was varied. The results of this test from which the cam ordinates required for any type of forcing function can be determined are shown in figure 3.

Because of the method used to pulse the air jets, the mass flow and velocity of the air through the nozzles are constant with frequency; thus, the force exerted on a surface should also be independent of frequency. This result is verified experimentally in figure 4 which shows that the oscillating force exerted on a flat plate is constant over the range of frequencies tested (0 to 500 cycles per second). It appears to be reasonable to assume that the force will remain constant at higher frequencies.

Since the oscillating force is constant from zero frequency, the force of the jets may be calibrated statically. Figure 5 shows the static force exerted on a large flat plate by the stream of air from a 0.0225-square-inch nozzle at a distance of 14 inches from the plate as a function of stagnation pressure. This force curve is fairly linear and shows the available force F to be approximately $1.5Ap_t$. The

idealized force exerted on a flat plate by a jet of air may be shown to

be $2Ap_t$ by combining the equations defining the rate of change of momen-
tum $F = w \, \Delta V$ and the stagnation pressure $p_t = \frac{1}{2} \rho V^2$ where $w = \rho AV$
and $\Delta V = V$ for the case of a flat plate. For the case for which
Pelton-type buckets have been added to increase the force output,
$\Delta V = 2V$.

Figure 6 indicates the manner in which the available force is
affected by the diameter of the specimen and the distance of the speci-
men from the nozzle. The maximum force is obtainable when the distance
to the plate is approximately equal to the plate diameter. These data
were measured without an interrupter disk between the nozzle and the
flat plate; hence, they do not show the effect of induced flow between
the plate and the disk. The induced flow between a 4-inch-diameter
interrupter disk mounted $\frac{1}{2}$ inch from a flat plate was found experimen-
tally to reduce the available force exerted on the plate by approximately
50 percent. The effect of induced flow became negligible at a distance
of approximately 2 inches from the interrupter disk to the plate.

For a shaker configuration, such as that shown in figure 1, it
would seem likely that the force of the airstreams impinging on the test
specimen could be reduced appreciably owing to the proximity of the edge
of the test specimen. Figure 7 indicates, however, that, for the
0.0225-inch nozzle tested, the axis of the airstream may be as close as
$\frac{1}{2}$ inch to the edge of a flat plate without resulting in any loss in the
available force.

In some instances it may be necessary to mount the shakers so that
the air jets strike the surface at an angle other than 90°. It was
found experimentally that the force normal to the plate varies as $\cos^{3/4}\theta$
whereas the force parallel to the jet varies as $\cos^2\theta$, where θ, the
angle between the flat plate and the plane normal to the axis of the jet,
is less than 45°.

A test was conducted on a single-degree-of-freedom system to deter-
mine the amount of damping, if any, attributable to the air jets. Fig-
ure 8 is a response curve obtained by using a single jet shaker. Four
values of the structural damping coefficient g were calculated from
the width of the response curve and one $\dfrac{x_{st}}{x_{max}}$ from the height of the
response curve. The values for g obtained from the width of the
response curve range from 19 to 38 percent greater than the value of
0.0182 obtained from a decrement whereas the value obtained from the
height of the curve indicates a 48-percent increase over the decrement
value. Similar tests using an electromagnetic shaker as the driving
force resulted in values for g that are 100 percent greater than those
obtained from decrements. The number of points required to obtain the
response curve of figure 8 indicates that the variable-speed friction

drive was satisfactory as a speed control for the pneumatic vibrator. The increment in frequency between some of these points was 0.05 cycle per second at a natural frequency of 49.1 cycles per second.

An application of an air-jet shaker is indicated in figure 9, which is an experimental frequency-response curve of a single-degree-of-freedom nonlinear spring. The nonlinearity in this case is in the form of free play as indicated in the inset. This condition results in a frequency-response curve which has an unstable branch similar to that described in reference 2. Branches AD and FI of the frequency-response curve (fig. 9) represent stable motion whereas branch DF represents an unstable motion which is not readily determined by experiment. If the oscillating force is kept constant and the frequency is gradually increased, the amplitude increases to the point D, suddenly drops to the point H, and then continues to the point I. With decreasing frequency the amplitude proceeds from the point I to the point F, suddenly increases to the point B, and then continues to point A; thus, the branch DF is undefined. If at the point C the amplitude is forcibly reduced by means of stops to a point just above point E, the spring, when released, will return to the original amplitude C. If, however, the amplitude is forced to a point below point E, the amplitude will immediately drop to point G. Repetition of this procedure will quickly establish the unstable point E. This procedure, in practice, is straightforward and was found to be repeatable with good accuracy. This method of defining the unstable branch of the frequency-response curve would be extremely difficult with a conventional shaker whose force varies with amplitude because of the difficulty of maintaining a constant driving force throughout the procedure.

APPLICATIONS OF JET SHAKER

Excitation of the true vibration modes of light wings or control surfaces is made difficult, if not impossible, because of the added mass of the shakers commonly available. The air-jet shaker described herein is ideally suited for vibratory tests on this type of model because of its essentially massless characteristics and because of its flat output with frequency. Its massless characteristic allows the shaker to be located at a point of maximum vibratory amplitude and thus maximum energy is transmitted to the elastic body.

The repeatability of vibration data obtained by using mechanical or electromagnetic shakers is often poor because of slight changes in the method of attachment and hence in the driving force. This difficulty is especially true of nonlinear systems where the frequency of the peak response is a function of the amplitude and, thus, of the driving force. This difficulty is eliminated by use of an air-jet shaker since there is no connection to the test specimen. Shaker tests of an elastic body are

considerably simplified with this shaker by the fact that no attachment
to the body is required, especially in cases where the shaker must be
moved frequently to avoid nodal lines. The measurement of frequency-
response curves is also greatly facilitated since no manipulation of
the flow-regulating valve is necessary to maintain a constant force
output as the frequency is varied.

In some instances, it may not be desirable or possible to mount a
shaker, as sketched in figure 1, on an edge of a test specimen such as
a skin panel. If the response of the test body is linear with driving
force, a shaker incorporating a single air jet and an interrupter would
suffice. If the response of the elastic body is nonlinear with driving
force, two single jet units may be mounted on opposite sides of the
surface and driven 180° out of phase.

CONCLUDING REMARKS

A shaker which obtains its driving force from streams of high-
velocity air is described. This shaker has the following advantages:
it is essentially massless; its available force can be easily calibrated
statically and is constant with frequency; no attachment to the test
specimen is required; and this shaker may be used in multiple-shaker
arrangements. With this shaker it is also possible to define the unstable
branch of a frequency-response curve obtained for a nonlinear spring.
If large force outputs are obtained with this shaker, much noise is
generated.

Langley Aeronautical Laboratory,
    National Advisory Committee for Aeronautics,
        Langley Field, Va., April 19, 1957.

REFERENCES

1. Bisplinghoff, Raymond L., Ashley, Holt, and Halfman, Robert L.:
    Aeroelasticity. Addison-Wesley Pub. Co., Inc. (Cambridge, Mass.),
    c.1955.

2. Den Hartog, J. P.: Mechanical Vibrations. Third ed., McGraw-Hill
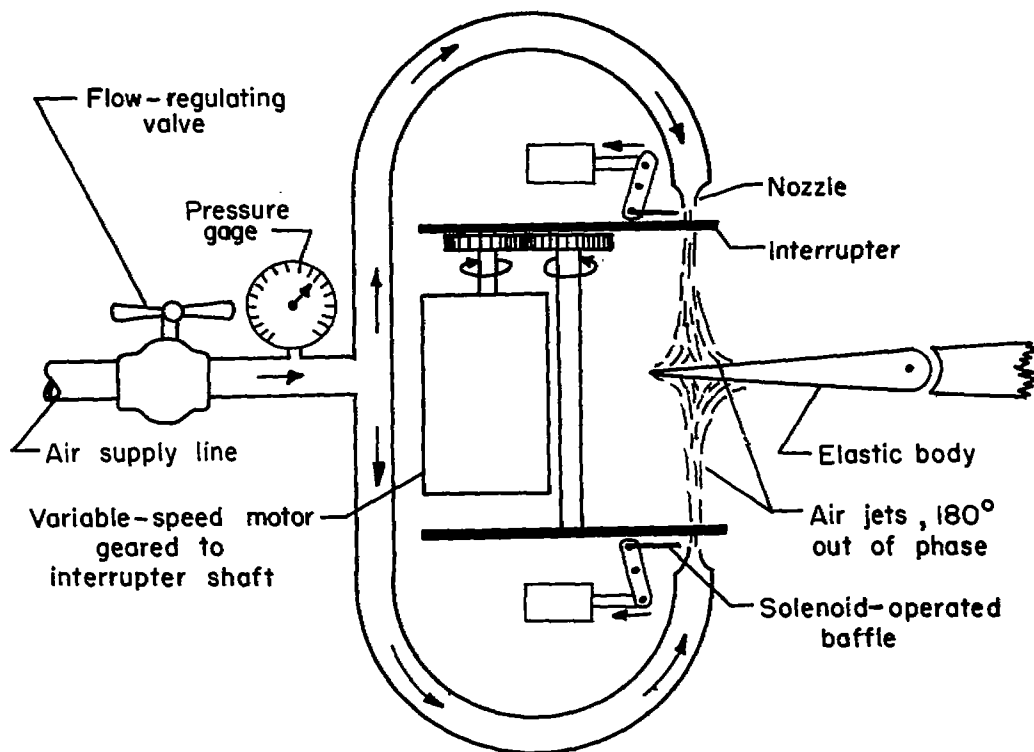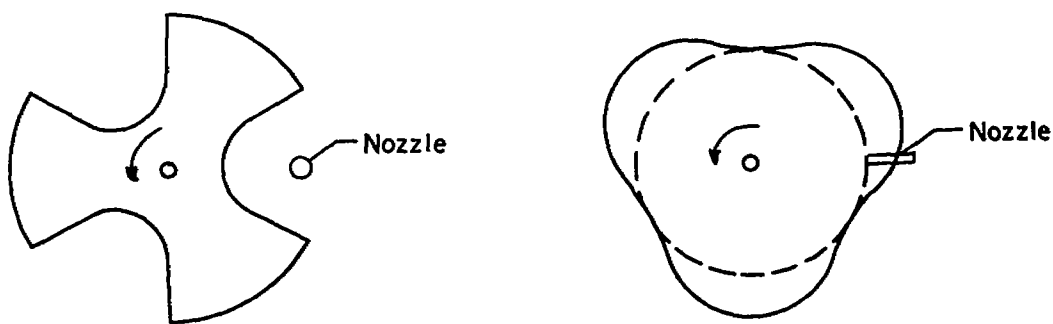   Book Co., Inc., 1947.

Figure 1.- Sketch of air-jet shaker.

(a) Square wave interrupter. (b) Sinusoidal interrupter.

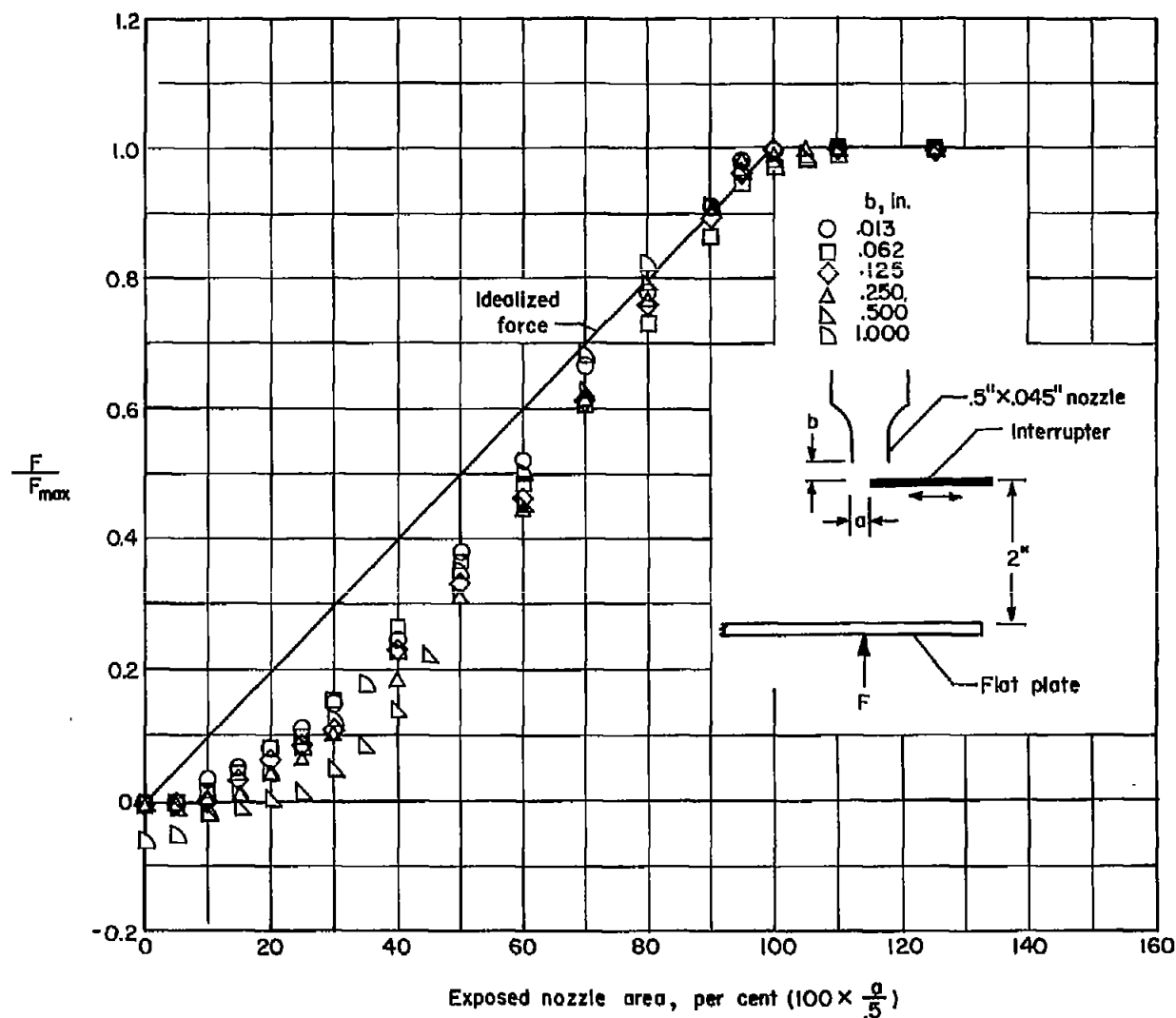Figure 2.- Sketch of interrupters and nozzles.

Figure 3.- Variation of available force with exposed nozzle area for various distances from nozzle to interrupter.
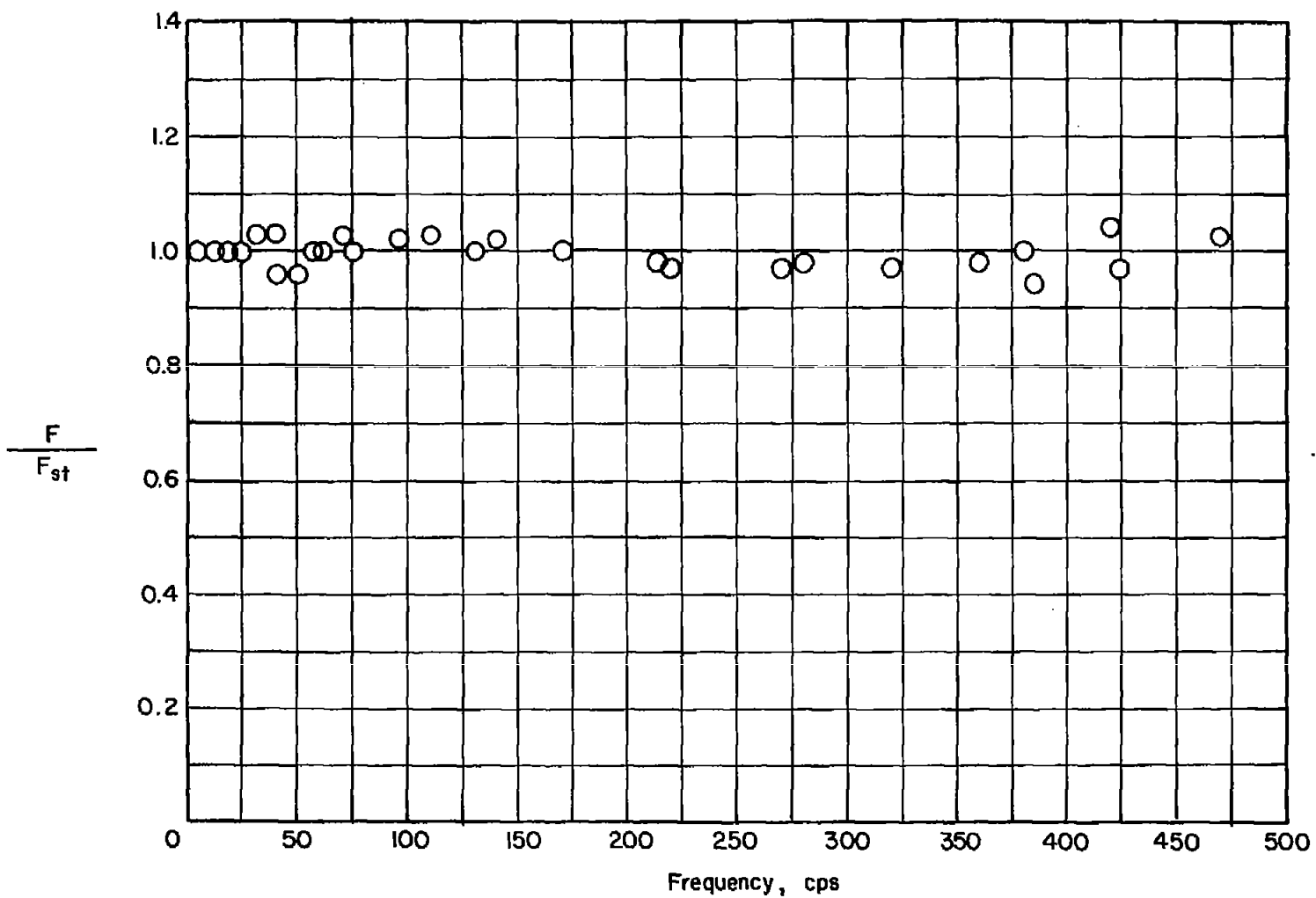
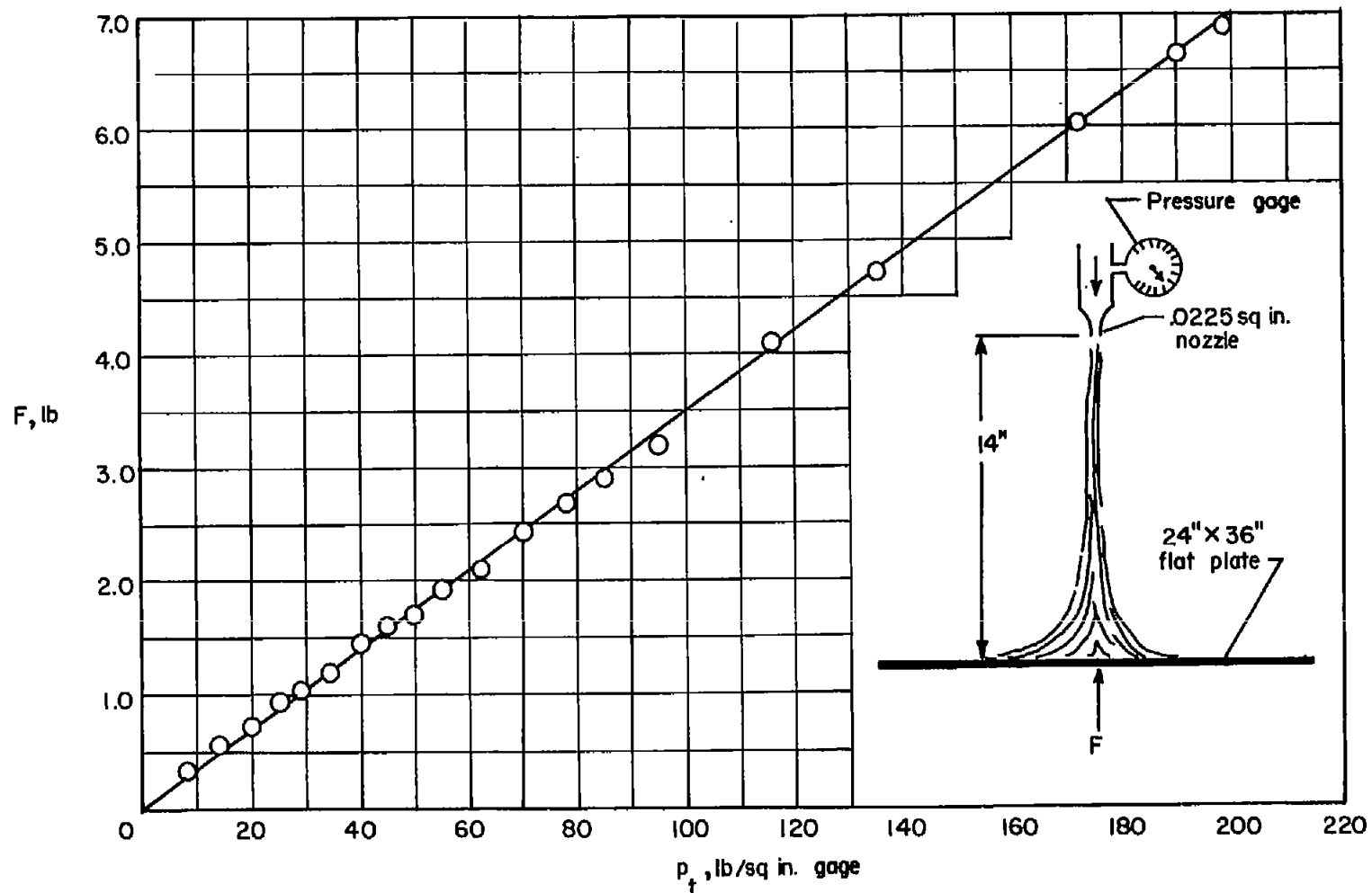Figure 4.- Force exerted on flat plate as function of frequency.

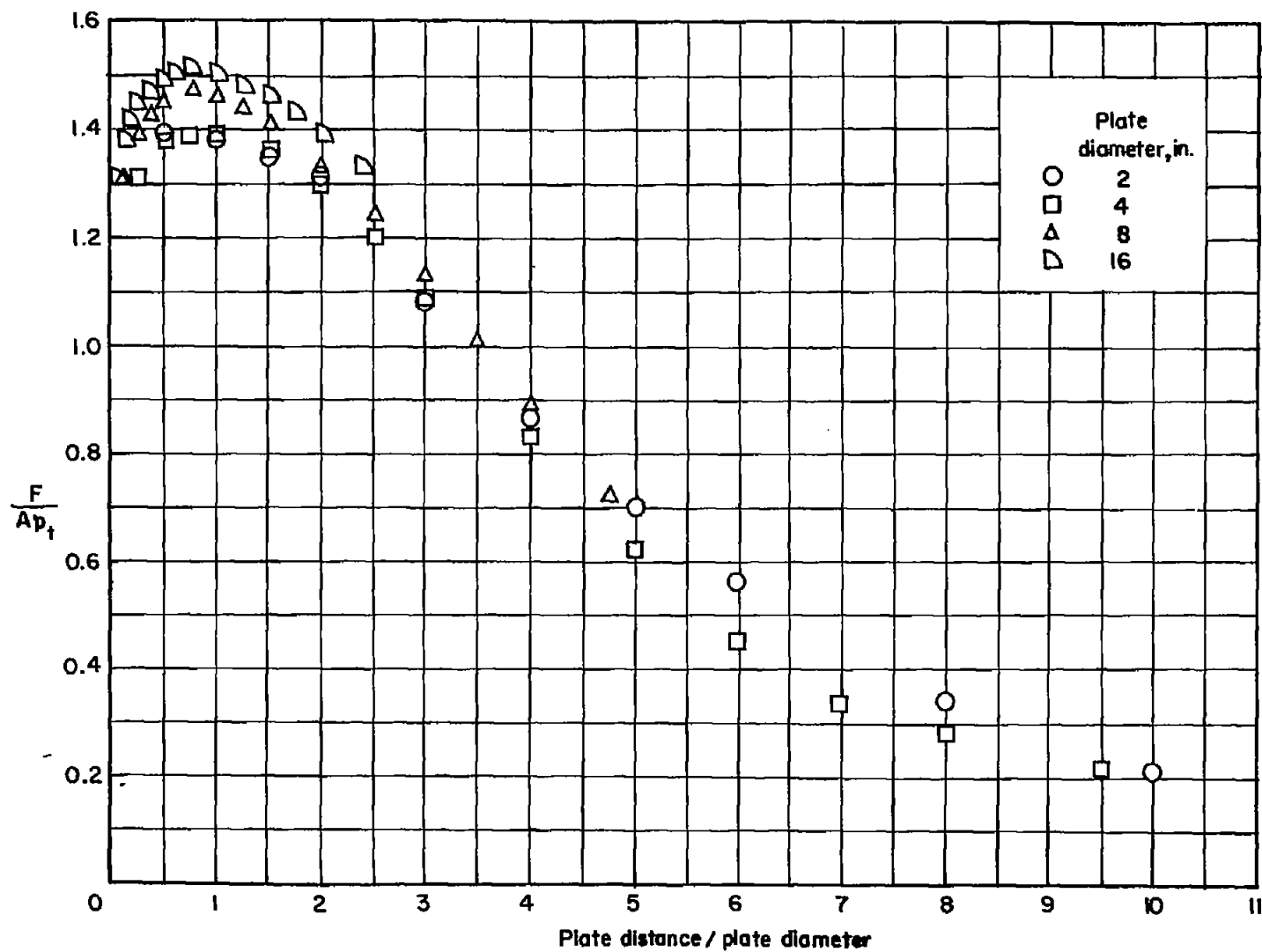Figure 5.- Variation of available force with stagnation pressure.

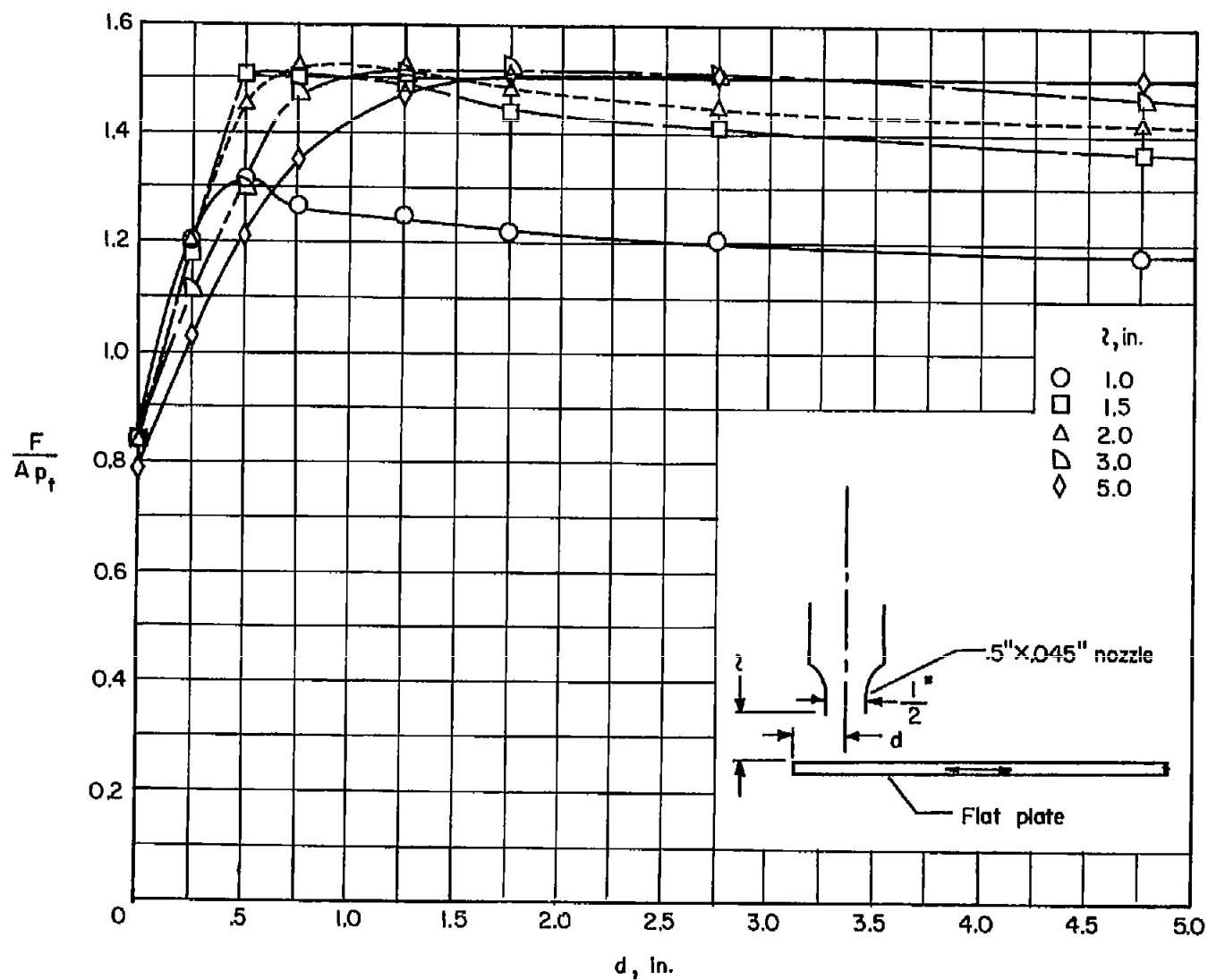Figure 6.- Force coefficient as function of the ratio of plate distance to plate diameter.

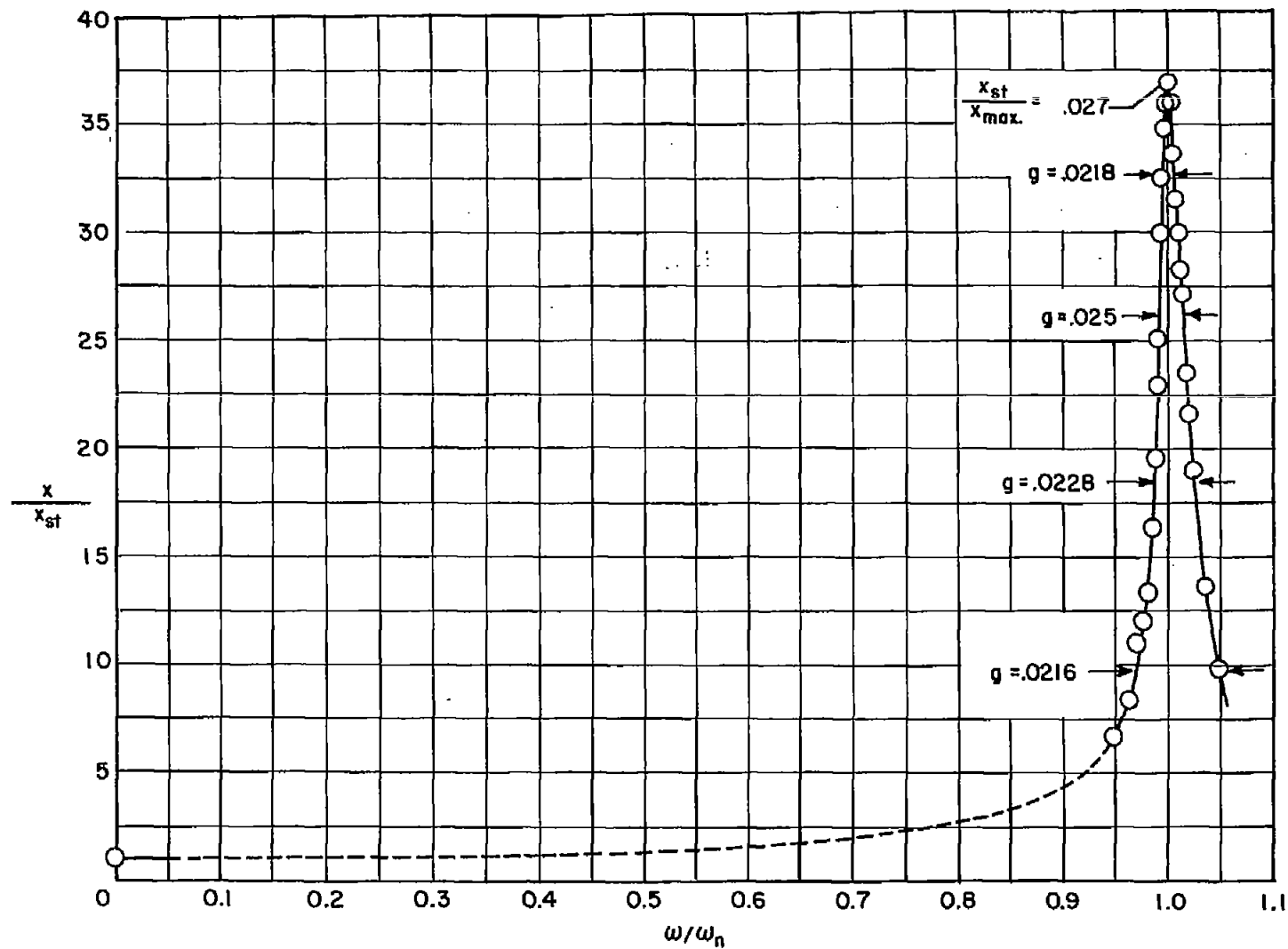Figure 7.- Variation of force coefficient with distance from center of jet to edge of plate.

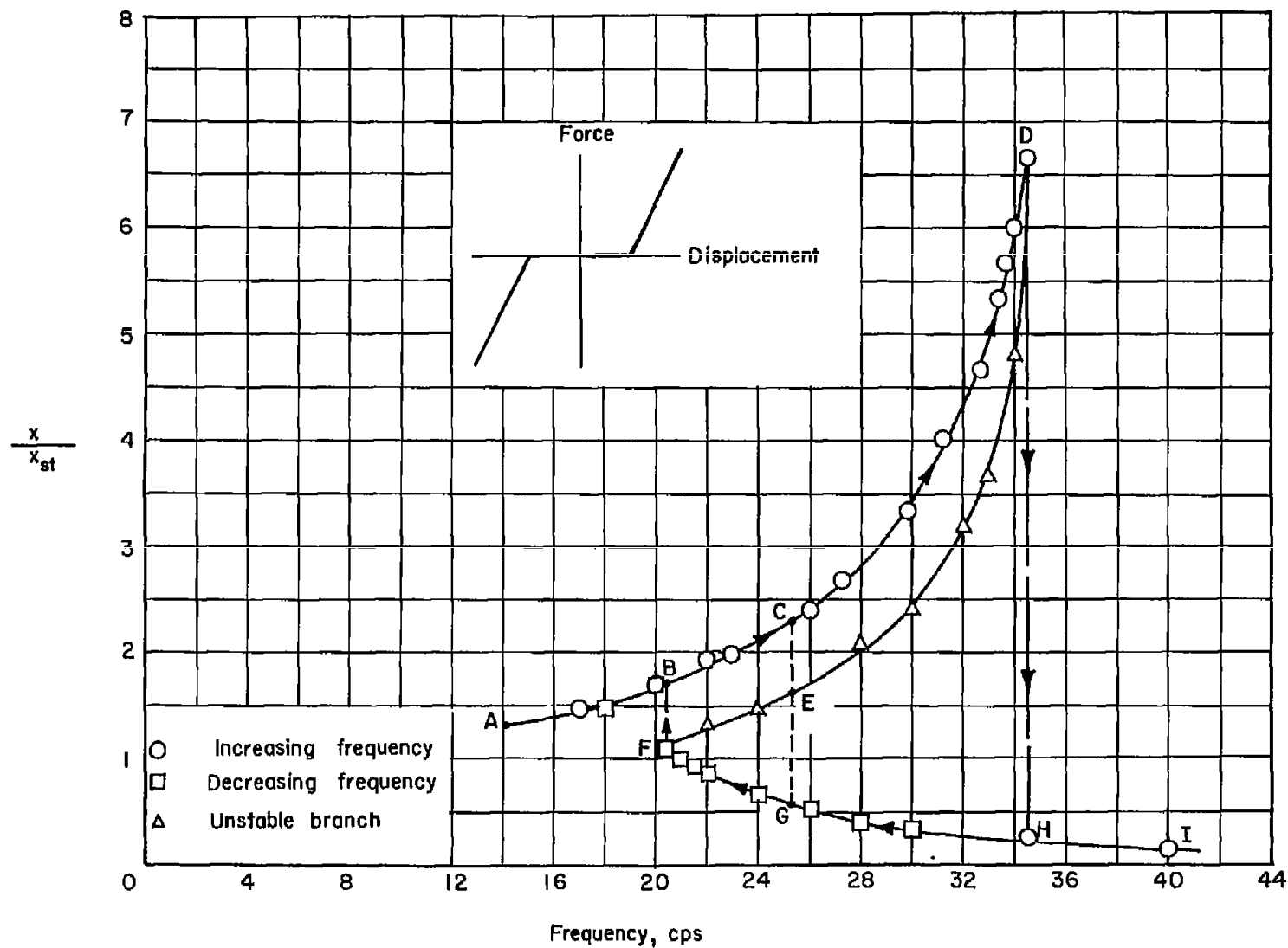Figure 8.- Single-degree-of-freedom response. Single jet shaker.

Figure 9.- Frequency response of nonlinear spring with unstable branch experimentally defined.